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Analysis of Electricity Usage for Domestic Heating Based on an Air-to-Water Heat Pump in a Real World Context

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Abstract In this paper a new computational model to estimate the performance of an air to water heat pump in relation to outdoor temperature is proposed and evaluated. This model is an extension and refinement of a model proposed in previous work. In the new model the following has been taken into account. Real empirical data for usage of a heat pump over a whole heating season have been used to obtain accurate parameter values. The energy which is used for heating sanitation water for the bathroom is taken into account in a separate submodel. According to some reports, around 15 % of domestic energy usage is for hot water. From the empirical data set, the fraction of energy which is consumed for this purpose is known, and it is used to model the usage for sanitation water heating as separate from the usage for heating. In this model the amount of energy which is used to keep the system working (active standby mode) is taken into account as well. The now available empirical data for the whole heating season have been used to estimate the parameter values for this model on the one hand and validation on the other hand.

1 Introduction

It is estimated that 43 % of the total energy usage in the European Union in 2006 was spent on heat related needs (cf. [1]). To reduce this part of energy usage, in addition to good isolation of the house, also domestic heating systems are considered, such as heat pumps that allow the use of renewable energy; e.g., [2]. They

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take most of their energy (up to 80 %) from the heat available in the ambient air, water or soil. The remaining energy usage concerns electrical energy to run the heat pump, which also can be produced based on renewable energy sources such as solar or wind energy.

Domestic heat pump users are facing a challenge to estimate their own energy usage on heating mainly because the performance indicators given by heat pump manufacturers do often not cover the dynamic conditions of using it (e.g., indoor and outdoor temperatures). This paper focuses on how an empirically validated computational model can be used to get this estimation in case of an air to water heat pump (because of using the air as a source, it also called as air source hear pump or ASHP).

In designing new houses or renovating existing houses nowadays, often an aim is to come as close as possible to an *energy neutral* or *net zero* house; e.g., [3–9]. In a net zero house, the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy created on the site. In such houses often a PV system is used to produce the needed energy as solar energy. A computational model as described here can be useful to estimate the annual energy needs and base the decision on the dimensions of the PV system on that (like [10]).

The energy demand for heating of a house strongly depends on the ambient temperature. It is common to model the heating demand in a linear manner as a function of the outdoor and indoor temperatures, proportional to the number of degree days: the sum of the differences of indoor and outdoor temperatures over time. For traditional heating systems, in general their energy usage is modeled as proportional to the heating demand, where the proportion factor indicates the energy efficiency of the system. These linear relations between energy usage and indoor and outdoor temperatures make it easy to aggregate and average the usage over time. For example, the average energy usage over some time period can be determined directly on the basis of average indoor and outdoor temperatures over this period.

For an air to water heat pump the energy usage also depends in a linear manner on the energy demand and through that on the indoor and outdoor temperatures. But an important difference is that also its efficiency of heating (expressed as its Seasonal Performance Factor, SPF) depends on the outdoor temperature. Therefore in the overall relation between energy usage and temperatures, these temperatures have a double and nonlinear effect on the energy usage [10]. As a consequence, taking averages over longer time periods does not provide adequate estimations: for every occurrence of an ambient temperature the energy usage has to be calculated separately. Therefore, in this paper, the variation of outdoor temperature over the year is analyzed and it is determined by simulation over days how this variation affects the energy needed for heating.

In the paper, first in Sect. 2 some background theory on heating based on a heat pump and a computational model are presented. Next, in Sect. 3 it is shown how parameters representing characteristics of a given house and of the heat pump can estimated based on empirical data. This provides a well-tuned model of the heat pump in the given house. Section 4 includes a discussion and future directions.

2 Background Knowledge and the Computational Model

In this section some background knowledge on domestic heating is discussed, and a computational model based on that. For domestic heating three important elements are:

- The characteristics of the heating system used; e.g., efficiency
- The characteristics of the house; e.g., how well isolated is the house
- The characteristics of the environment; e.g., the outdoor temperature.

To estimate the *efficiency* of a heat pump often the Seasonal Performance Factor, *SPF,* is used (usually for a particular period of time or a season) [11–13]:

$$SPF = \frac{energy\ provided}{energy\ used}$$

For air to water heat pumps in the marketplace, the Seasonal Performance Factor usually varies between 2 and 5 (e.g., for outdoor temperatures between −5 and 15 °C) [14]. Often it is between 3 and 4 (e.g., for ambient temperatures between 0 and 10 °C). In general, *SPF* is approximated by a mathematical function of the outdoor temperature T_{od}. Often a linear approximation is used; (e.g., [15, 16]), and the *SPF* for a given day is based on the average day temperature. For this paper the following new steps are made:

1. Not the average day temperature is used but the minimum and maximum day temperatures, T_{odmin} and T_{odmax}
2. As an approximation of *SPF*, a quadratic function in T_{odmin} and T_{odmax} is used
3. The parameters of this quadratic approximations are estimated based on a large real world empirical data set, available from the website http://www.liveheatpumps.com

Based on these steps the model for *SPF* gets the format

$$SPF = A + BT_{odmin} + CT_{odmax} + DT^2_{odmin} + ET^2_{odmax} + FT_{odmin}T_{odmax}$$

where the parameters *A* to *F* are tuned based on real world empirical data (see Sect. 3). Since $SPF = \frac{energy\ provided}{energy\ used}$ the energy usage can be easily determined from the energy demand:

$$energy\ usage = \frac{energy\ demand}{SPF}$$

The *energy demand for space heating* of the house also depends on the ambient temperature. To model this, the following linear function of the temperature differences has been used.

$$\textit{energy demand for space heating} = B_1(T_{idavg} - T_{odmin}) + B_2(T_{idavg} - T_{odmax})$$

Here T_{idavg} is the average indoor temperature over 24 h, and B_1 and B_2 are parameters relating to the energy loss and to the role of lower and higher temperatures during the 24 h. This expression can easily be rewritten into:

$$\textit{energy demand for space heating} = \varepsilon(T_{idavg} - (wT_{odmin} + (1-w)T_{odmax}))$$

$$\textit{with } \varepsilon = B_1 + B_2 \text{ and } w = B_1/(B_1 + B_2)$$

Here ε is the energy loss per degree day, and w is a weight factor between 0 and 1. These are parameters of the house estimated in Sect. 3.

Together the above formulae provide the following model for *daily energy usage for space heating*:

$$\frac{B_1(T_{idavg} - T_{odmin}) + B_2(T_{idavg} - T_{odmax})}{A + BT_{odmin} + CT_{odmax} + DT_{odmin}^2 + ET_{odmax}^2 + FT_{odmin}T_{odmax}}$$

The energy demand for *heating of sanitation water* follows different patterns. Most of it depends on when and how much of this water is used. This is difficult to predict for each day separately, so it is considered to be an average value with fluctuations around it. However, there is also a slight dependence of the demand on outdoor temperature. Therefore this has been modeled as a linear function of the maximum and minimum outdoor temperature:

$$\textit{energy demand for sanitation water} = A_1 + A_2T_{odmin} + A_3T_{odmax}$$

So the *daily energy usage for sanitation water* is modeled by

$$\frac{A_1 + A_2T_{odmin} + A_2T_{odmax}}{A + BT_{odmin} + CT_{odmax} + DT_{odmin}^2 + ET_{odmax}^2 + FT_{odmin}T_{odmax}}$$

Finally, the system has a default usage per day for its *active stand by function*, therefore a constant value S is added. Thus the overall model becomes:

$$\begin{aligned} \textit{overall day energy usage} &= \textit{active stand by usage} + \textit{energy usage for space heating} \\ &\quad + \textit{energy usage for sanitation water} \\ &= S + \frac{B_1(T_{idavg} - T_{odmin}) + B_2(T_{idavg} - T_{odmax}) + A_1 + A_2T_{odmin} + A_3T_{odmax}}{A + BT_{odmin} + CT_{odmax} + DT_{odmin}^2 + ET_{odmax}^2 + FT_{odmin}T_{odmax}} \end{aligned}$$

3 Tuning the Computational Model to a Real World Situation

In this section it will be discussed how the parameters of the introduced computational model have been estimated based on real world data for a specific type of heat pump, a specific house, and its specific environment.

To tune the parameters in such a way that results of our model match to the real world data, interior-reflective Newton method, described in [17, 18], have been used. Moreover, to get rid of the local optimum answers, for each set of parameters, the algorithm was run for 1000 times, and the best set of parameters (with minimal error) is reported in this paper.

The parameters can be partitioned into two groups:

- Parameters representing characteristics of the heat pump: the parameters in the model for SPF (A to F)
- Parameters representing characteristics of the house and its environment: the parameters used in the models for sanitation water heating and space heating demand (A_1, A_2, A_3, B_1, B_2).

3.1 Real World Datasets

In this work two different sets of real world data were used to tune the parameters of the proposed model. These datasets come from two houses which are equipped with the same type of heat pump considered (Fujitsu General Waterstage WOH14RIYF/WH16).

- **Dataset of house1**: This house is located in Lembeek, Belgium (about 50.4 latitude, 4.1 longitude). The empirical data for performance characteristics and outdoor temperatures of this house can be found at http://www.liveheatpump.com. From this Website empirical data on performance and daily maximum and minimum outdoor temperatures have been collected for this site for the period October 2013 to April 2014.
- **Dataset of house2**: This house concerns a reasonably well isolated three storey family house near Alkmaar, The Netherlands (about 52.6 latitude, 4.7 longitude). It is a netzero house using the aforementioned type of heat pump for space heating and heating of sanitation water. Daily data of minimum and maximum temperatures and energy usages of the heat pump for a whole year are available in this dataset. However, it is known that in the period from June to September, no space heating takes place, while in period of November to March, energy is used for both sanitation water and space heating. In the months April, May and October only occasionally space heating takes place.

3.2 Parameters Representing Characteristics of the Heat Pump

The data set of house 1 was used to estimate the parameters which represent the performance characteristics of the heat pump: the SPF. The outcome was:

$$A = 1.9869\ B = 0.1419\ C = 0.0053\ D = 0.1113\ E = -0.0024\ F = -0.0096$$

The following averages have been found:

Average of Absolute Error = 0.1566
Average of Relative Error = 0.0492
Average of Absolute Error/Average of *SPF* = 0.0487

In Fig. 1 it is shown how the obtained approximation follows the real values over the days.

3.3 Parameters Representing Characteristics of the House

As a next step, it is discussed how parameters involving characteristics of the house were estimated. First, the energy demand for heating of sanitation water is addressed. Empirical data of house 2 on daily usage were used for the period June to September, in which no space heating took place. So, all usage is for the active standby and for heating of sanitation water. From the days that no heating of

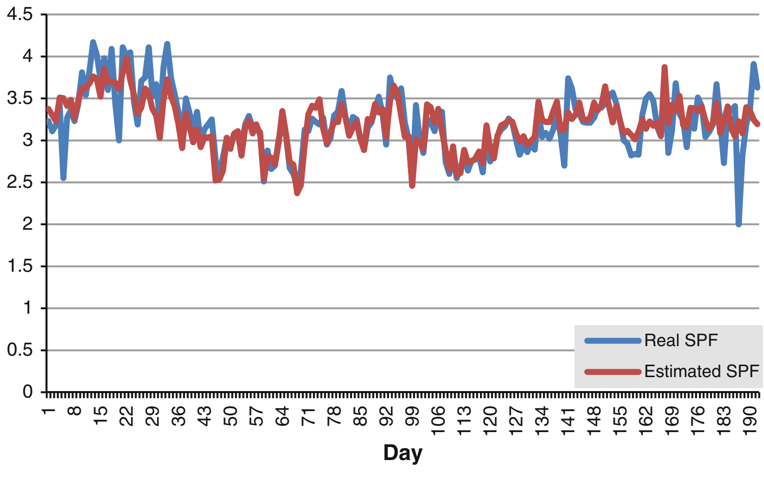

Fig. 1 Daily performance factors of the heat pump system for house 1: estimated versus real values

sanitation water took place it was found that the active standby takes 0.4 kWh per 24 h, so parameter S = 0.4. This value was subtracted from all values to remain the daily usages for sanitation water. These were used to estimate the value of parameters A_1 to A_3 for the water heating. The outcome was:

$$A_1 = 2.7275 \quad A_2 = -0.0210 \quad A_3 = -0.0481$$

Over the days of the considered time period the following averages have been found.

Average Real Sanitation Water Heating over Days = 0.8270
Average Predicted Sanitation Water Heating over Days = 0.8229
Deviation Predicted—Real Sanitation Water Heating Average = −0.0041 (= −0.5 %)
Average Absolute Error in Sanitation Water Heating over Days = 0.2542
Average Relative Error in Sanitation Water Heating over Days = 0.4059
Average Absolute Error over Days/Average Usage for Sanitation over Days = 0.3089

In Fig. 2, it is shown how this model approximates the real values of energy usage for water heating plus the 0.4 for active standby. Note that the deviations are mainly due to the unpredictable character (fluctuations) of the use of sanitation water.

After this, the average of the indoor temperature T_{idavg}, and the parameters B_1 and B_2 for the space heating model were estimated using the empirical data for the period November 2013 to May 2014. The values found are:

$$T_{idavg} = 17.3834 \quad B_1 = 0.8572 \quad B_2 = 1.9865$$

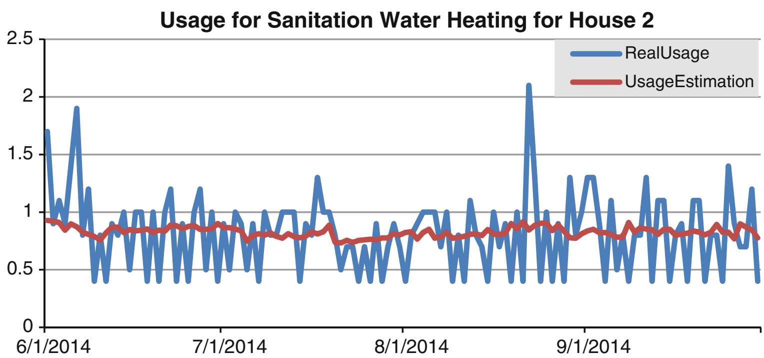

Fig. 2 Energy usage for sanitation water heating (and active standby), for house 2 from June to September 2014

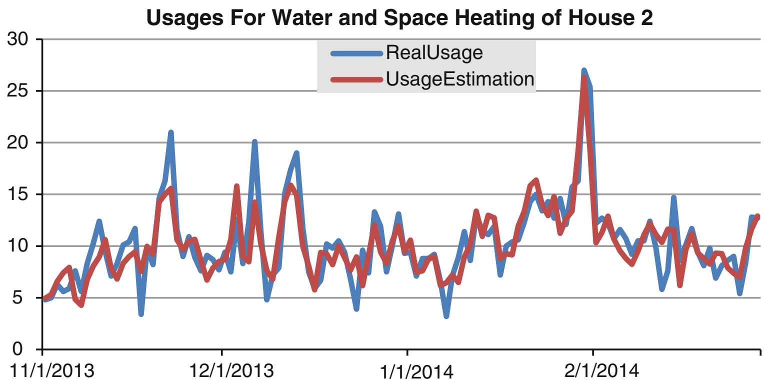

Fig. 3 Energy usage for both water and space heating (and active standby) for house 2, from November 2013 to March 2014

This entails

$$\varepsilon = 2.8437 \quad w = 0.3014$$

Over the days of the considered time period the following averages have been found for heating of sanitation water plus active standby:

Average Real Overall Usage over Days = 9.6396
Average Predicted Overall Usage over Days = 9.6617
Deviation Predicted - Real Overall Usage Average = 0.022 (= 0.2 %)
Average Error in Overall Usage over Days = 1.566
Average Relative Error in Overall Usage over Days = 0.1975
Average Error in Overall Usage over Days/Average Usage over Days = 0.1625

Figure 3 shows the results of the proposed model and the real value of overall daily usages for the period November 2013 to March 2014.

4 Discussion and Conclusion

In this paper, a new model is proposed to estimate the energy usage of an air to water heat pump system used for domestic heating purposes. The model can be used to perform simulations on energy usage of the heat pump day by day for arbitrary time periods (e.g., seasons or years). The model includes a number of parameters representing characteristics of the type of heat pump, the house and of the environment. It was shown how appropriate values for these parameters can be found to tune the model to the characteristics of a specific type of heat pump, and of a specific house and its environment. The data obtained by simulation of the model have been compared to real world data, and the error has been estimated.

The overall evaluation can be done through different evaluation measures. The average relative error in the model for the estimation of *SPF* based on minimum and maximum temperatures is 5 %. For the computational model for the heat pump usages, when evaluated for averages over a longer time period (for example, one year or one heating season), the computational model provides quite accurate predictions. For example, for the time periods considered in Sect. 3 the relative deviation between predicted and real average usage for sanitation water heating was 0.5 % and for overall usage of the heat pump the relative deviation was 0.2 %. However, predictions for specific days are less easy due to inherent day-by-day fluctuations. The average relative error in the prediction of usage for sanitation water heating over days is 40 %, while it is 20 % for overall usage (both water and space heating). One reason for a deviation in prediction of usage for a particular day is that in the considered house there is no fixed daily heating program. In fact, some days, nobody is in the house; therefore the space heating is off and thus does not keep the house on a higher space temperature. On other days, always somebody is in the house, and the temperature is kept high between 7 A.M. and 9 P.M. These fluctuations by themselves are an inherent source of error. By its design the model had no information about them and therefore was not able to take them into account. Given these sources of inherent error, an average error below 20 % could be considered not bad at all.

In future, this model will be validated with more empirical data. Moreover, an effort will be done to compare the accuracy of this model to that of a number of other existing models. Furthermore, it may be considered in how far the inherent fluctuations in demand both for sanitation water and space heating can be included in the model by adding log data on the behaviour of the persons in the house: e.g., when they are present, and when they use the bathroom.

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